U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-260 153

PRELIMINARY WATER POLLUTION CONTROL STUDY COLORADO RIVER BASIN ABOVE HOOVER DAM

APPENDIX A. REVIEW OF DEVELOPMENTS, METHODS, COSTS AND CONTROLS. A-1. EVAPORATION A-2. PHREATOPHYTES. A-3. DESALINATION

PUBLIC HEALTH SERVICE, DENVER, COLORADO

MAY 1965

PB 260 153

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No. PB-260 153
4. Title and Subtitle Preliminary Water Pollution Control Study. Colorado River Basin Above Hoover Dam. Appendix A. Review of Developments, Methods, Costs and Controls. A-1. Evaporation. A-2. Phreatophytes. A-3. Desalination.			5. Report Date May 65 6.
7. Author(s)			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Public Health Service, Denver, Colo. Div. of Water Supply and Pollution Control.			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address			13. Type of Report & Period Covered 14.

15. Supplementary Notes

Report on Colorado River Basin Water Quality Control Project.

16. Abstracts The three appendices review the developments, methods, costs, and controls related to evaporation, phreatophytes, and desalination. Each of these areas is explored separately with their own bibliographies included. Evaporation is discussed in terms of the importance of evaporation losses, types of control, area reduction, mechanical covers, surface films, the history of films, and U. S. evaporation control studies. Past and present interest in phreatophytes and their use of water is discussed in some detail. It is concluded that the future of saline water conversion in providing high quality water will be limited to the area of water treatment, and is not likely to be used as a salinity control procedure for maintaining in-stream water quality.

17. Key Words and Document Analysis. 17a. Descriptors

17b. Identifiers/Open-Ended Terms

Hoover Dam
Colorado River
*River basins
*Water pollution control
*Water pollution sampling
Cost estimates
Desalinization
Evaporation control
Salinity
*Water treatment

17c. COSATI Field/Group 13B

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 47
	20. Security Class (This Page UNCLASSIFIED	22. Price

PRELIMINARY WATER POLLUTION CONTROL STUDY
COLORADO RIVER BASIN ABOVE HOOVER DAM

APPENDIX A
REVIEW OF DEVELOPMENTS, METHODS, COSTS & CONTROLS

A-1 EVAPORATION

A-2 PHREATOPHYTES

A-3 DESALINATION

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Bureau of State Services
Division of Water Supply and Pollution Control
Region VIII
Denver, Colorado

Colorado River Basin Water Quality Control Project

May 1965

APPENDIX A-1

REVIEW OF DEVELOPMENTS, METHODS COSTS AND CONTROLS

EVAPORATION

REVIEW OF DEVELOPMENTS, METHODS, COSTS AND CONTROLS

-1 EVAPORATION

Importance of Evaporation Losses

The importance of evaporation losses from free water surfaces in reservoirs, ponds, lakes, and canals in the seventeen western states is becoming more acute each year as the demand for water continually increases. The increasing demand is due to several factors[1] including increases in population, industrial activity in the West, development of irrig ble lands, and increased per capita demand and consumption due to higher standards of living.

For many years, evaporation rates were of academic interest because nothing could be done to conserve the water. However, with the development of a process that provides hopes for successful control, the importance of evaporation and potential savings take on quantative and practical significance.

Meyers[2] has estimated that the total evaporation from reservoirs, lakes, ponds, streams, and canals in the seventeen western states is 23,641,000 acre-feet. The evaporation from salt water areas is an additional 17,565,000 acre-feet. These are annual evaporation rates.

Some of these losses are from rivers and streams for which there is no practical control. Many of these sources can be controlled by evaporation suppressants, and since these losses are large, the potential for water conservation is large. The losses in the Colorado River Basin are 2,200,000 acre-feet. Over half of this loss is from principal reservoirs and regulated lakes on the Colorado River in the Lower Basin (below compact point). Meyers' figures do not include losses from recently completed reservoirs such as Lake Powell, Navajo and Flaming Gorge.

The financial losses from these evaporation losses are difficult to assess. They are complicated by several factors. One is that the net evaporation loss is something less than the value given above since there would be some evaporation loss even though these large reservoirs were drained. Another factor is that many benefits have been gained from the storage of water. The relationship between damages incurred by increased evaporation losses and the benefits gained by storage is difficult to assess and is not the purpose of this report.

Types of Control

The variables that effect the rate of evaporation are solar radiation, wind movement, and the vapor pressures in the film of air next to the water surface and in the air above the film. The types of controls used to modify these variables and suppress evaporation rates by reducing the area of liquid-air interface can be divided into three categories: (1) reduction of surface areas; (2) mechanically covering the area; and (3) use of surface films. Of all these methods, the films have received most consideration since they seem to offer the greatest potential benefits. A brief review will be made of other methods, however.

Area Reduction

This can be accomplished in several ways. One method is by developing deep reservoirs having small surface areas as opposed to large shallow reservoirs. Another method is by developing one large reservoir, where possible, in favor of a number of smaller ones. It can also be accomplished by using underground storage, thus eliminating free water surface.

Freese[3] states that it was economically feasible to dike off a shallow area of Lake Worth, Texas, to eliminate 112 acres of water surface.

According to Thomas[4], the use of certain ground water reservoirs deserves a larger place in plans for complete waste water development. He qualified this by stating that this cannot be done - "until hydrologic knowledge is sufficient to show the way to successful manipulation of ground water storage."

Although surface evaporation is eliminated by ground water storage, a loss to phreatophyte growth may be incurred. Control of phreatophytes is the subject of another part of this report.

Mechanical Covers

Beatle[5] states that mechanical covers include fixed roofs, floating rafts, and wind breaks. These are not practical for very large reservoirs for fairly obvious reasons. The rafts, of course, would prohibit recreational use of lakes and ponds. Fixed covers have been used to cover finished water storage reservoirs, but more for protection from airborne pollution than to prevent evaporation. Harbeck[1] states that - "Leon Fine and associates have applied for a patent for a 'Reservoir water covering structure', which is a cover made of plastic. No information is available as yet concerning the cost of such plastic film, or whether the inventor considers it suitable for use in large reservoirs."

Another mechanical cover that is an innovation of plastic material is the use of plastic balls. Block[6] reports that in an experiment in which small, white polyethelene balls were used to reflect the sun rays, there was a reduction in water temperature and evaporation. The advantage of using balls is that after a disturbance of the water, the balls would redistribute themselves over the lake. Also, they could easily be removed from the water in the event if was necessary to do so. Block also described an incident where calcium carbonate particules were disbursed

through the surface brine of the Dead Sea during August 1963. The water turned milky-white. By October it was found that the sea level was rather high (presumably from evaporation reduction) and the temperature of the water at a depth of 15 meters was abnormally low. This was attributed to the reflection of the sun rays from the white surface.

The above-mentioned methods are practical in only specific instances and some are of nebulous value.

Surface Films

The general feeling of experts in the field of evaporation control is that films offer the greatest potential in the field of evaporation suppression. They are divided into three categoreis (1) oils (hydrocarbons), (2) multimolecular films, and (3) monomolecular films. Of these three types, the most effective and promising is the monomolecular film.

History of Films

Magin[7] provides a brief history of film development in his review of literature on evaporation suppression.

Agnes Pockels[8] discovered the formation of monomolecular surface films of spreading oils in 1891. Lord Rayleigh[9] in 1899 reviewed Miss Pockels' work and concluded that the oil spreads to form a film one molecule in thickness. Henri Devaux[10], during 1903-13, studied the effect of film on water and the limits of expansion. He concluded the film was only a single layer of molecules, and that the film could be stretched to a certain point, but which would disappear when stretched any thinner.

A series of investigators for the next forty years (Du Nouy, Hederstrand, Rideal, and Langmuir) debated the value of monolayer films as evaporation suppressants. Simultaneously, the effects of pure hydrocarbon oils (having no functional groups) on evaporation were being investigated

by Langmuir[11]. He found that these oils do not spread on water but form lenses. In other articles [12,13,14], he decided that in a monolayer, evaporation resistance is due to an energy barrier, but that in oil layers evaporation reduction is caused by a different mechanism. Langmuir[11] was the first to show that compounds with a hydrophobic paraffinic long-chain and a hydrophylic carboxyl radical would orient themselves at the air-water surface. Unfortunately, many are not suitable for field use, and although he showed that they were efficient in reducing evaporattion, William Mansfield[15], of Australia, is generally given credit for having first demonstrated the effectiveness of specific compounds in reducing evaporation from reservoirs under field conditions.

Evaporation Control Studies in the United States

Since the initial work in Australia reported by Mansfield, considerable work has been conducted around the world. Much work has been done in the USSR and the United States. The latter is of primary interest because it is available and corresponds more nearly to meteorological conditions of the Colorado River Basin, and the economic evaluations are more applicable to this area.

Cruse[16] and Stephens[17] reported on the aspects of a research project of the Southwest Research Institute in San Antonio, Texas. The research project was supported by thirteen interested organizations and included the preparation of a bibliography on the subject, an investigation of the relative potential of 152 compounds and compositions as evaporation retardants, and concurrent laboratory tests with hexadecanol in ten-foot stock tanks. The homologous straight-chain fatty alkanols, particularly hexadecanol and octodecanol, were considered the best materials for retardants. It was concluded from these studies that the major practical

problems to be overcome were the adverse effects of wind on the monofilms, the biochemical oxidation of the films, and difficulties in application. In addition to these, there were fundamental problems to be solved such as the effects of impurities, and the compostion of the evaporation retardant that would optimize all factors including toxicity to users and aquatic life, effects on limnology, maintenance of gas transfer phenomena, and resistance to bacterial and chemical decomposition of the films. The same report contains a summary of miscellaneous laboratory studies that were initiated, but they draw no quantitative conclusions.

Timberline[18], et al, reported on U. S. Bureau of Reclamation evaporation reduction studies. One project was carried out in four-foot diameter standard U. S. Weather Bureau Class A evaporation pans. One hundred twenty-five materials were tested and hexadecanol showed outstanding properties. Hexadecanol flakes were sprinkled in one pan at a rate of 60 pounds per acre, and a single application was effective for more than four weeks. A maximum efficiency of 64 percent was obtained. The results with hexadecanol varied from 10 to 60 percent evaporation reduction. Studies with hexadecanol and larger tanks (33 ft. x 10 ft.) resulted in evaporation reductions of 13 to 16 percent.

The more well-known and large field stdues in evaporation control have been those in Lake Hefner, Oklahoma City, Oklahoma, at Lake Cachuma Reservoir in Santa Barbara County, California, and at Lake Sahuaro on the Salt River about 40 miles east of Phoenix, Arizona.

The first large scale field study was at Lake Hefner[19]. This lake was selected because of size (2,500 acres), geographic location, meteorological conditions, and the fact that a detailed water budget including evaporation losses had been determined. Lake Hefner serves as part of

the water supply for Oklahoma City. Therefore, prior to the conduct of full scale studies on Lake Hefner, preliminary tests were made on Kids Lake to determine whether any adverse effects could be expected from the hexadecanol that would preclude the use of Lake Hefner. Kids Lake, an arm of Lake Hefner, had been closed off and was hydrologically independent of Lake Hefner. Gartska[18] reports that the results of the Kids Lake test indicated that there were three main problems that had to be solved before Lake Hefner studies could begin. These were methods for dispensing the chemicals, for maintaining a monolayer, and for detecting and evaluating a monolayer. These problems were worked out subsequently in reservoir studies in the Denver, Colorado, area. The Committee of Collaborators[19] in its report on the Kids Lake Study said that - "insofar as criteria of water quality, including taste, odor, color, toxicity, and other chemical qualities are concerned, nothing has been determined from this study to preclude further considerations of Lake Hefner for larger scale evaporation reduction investigations."

During the Lake Hefner project, many variables studied did not have a direct effect on evaporation reduction, but were nevertheless important. Some of these were effects of hexadecanol on water quality, lake biota, bacterial population, wild life, and recreation. Also included was an economic evaluation and an evaluation of hexadecanol formations containing various disinfecting agents.

Riesbol[19], in the economics evaluation of the Lake Hefner study states that the cost per acre foot of water saved ranged from $58 to $86 during the summer period, and averaged $61.20 for the entire summer. This cost is very close to the value of raw water in Lake Hefner, a value which the City of Okalhoma reports to be about $60.

About 40,000 pounds of hexadecanol were used during the test period July 3 to October 1, at a material cost of $4,313.13, unit cost of $0.515 per pound. This represented 73.5 percent of the total operation cost of $6,263.60. The overall reduction in evaporation during this period was computed to be 9 percent.

Silvey[20] reports that the destruction of hexadecanol by bacteria is more of an economic problem than a public health problem. At temperatures over 26°C, the amount of hexadecanol destroyed by bacteria increased in geometric ratio with time, i.e., of the hexadecanol required the first three-week period twice as much was required during the second three-week period and four times as much during the third three-week period, etc. This indicated the marked need for incorporating bacteriacides in evaporation suppressant formulations.

These results are also discussed by Chang[22], Berger[21], and Ludzack[23].

The second large field test was carried out on Lake Sahuaro[24], a 1,260 acre lake on the Salt River, 41 miles east of Phoenix, Arizona. About 7 feet of water are lost annually from this reservoir. About 12,000 pounds of hexadecanol were applied to the lake during the summer of 1960. During the test period from October 1 to November 17, the total treatment cost was $7,400. About 52 percent of this was the cost of materials. The cost varied from $58 to $69 per acre-foot saved. These studies were made during the period of relatively low evaporation, and it was computed that for similar material, labor and equipment costs, but for increased evaporation rates, the costs could be reduced from about $58 to $33 per acre-foot saved.

The third large Government sponsored investigation into evaporation controls on reservoirs was carried out in 1961 on Lake Cachuma Reservoir[25] in Santa Barbara County on the Santa Ynez River. About five to six feet of

water are lost annually from this 3,090 acre reservoir. The film layer daily coverage was usually from 20 to 60 percent and at times as high as 90 percent of the lake surface. Almost 60,000 pounds of the chemical were applied from July 20 to September 25, 1961. It was composed of 66.2 percent octodecanol, 30.4 percent hexadecanol, 3.3 percent tetradecanol, and 0.1 percent dodecanol.

During the summer, the evaporation saving was 257 acre-feet, or about 8 percent of the evaporation that would have occurred without control. The unit cost of control was $67.55 per acre-foot for materials, labor and equipment.

It is difficult to compare the results of these three field studies because of different meteorological conditions, especially wind speeds. The wind speeds averaged above 7 miles per hour at Lakes Hefner and Cachuma during the test periods, and the savings obtained were less than 10 percent. At Lake Sahuaro, the average wind speed was less than 5 miles per hour and there was a 14 percent savings on evaporation. This indicated the marked effect that wind can have on the effectiveness of these film layers.

A summary of the various costs and efficiencies for these three studies is shown in the following table.

TABLE A1-1

	Lake Hefner	Lake Sahuaro	Lake Cachuma
Chemical cost per pound	$ 0.515	$ 0.25	$ 0.215
Total cost of project per acre day	0.14	0.17	0.129
Cost per 1000 gallon water saved	58.00-86.00	58.00-69.00	67.55
Efficiency - percent water saved	9%	14%	8%

Franzini[26] states that the cost of chemicals for evaporation control is about $15-25 per acre-foot saved, and the cost may be decreased considerably as the demand for the chemicals increases. He states that it is possible now to save water at a cost of $20-35 per acre-foot on select reservoirs, having proper size and shape and located in areas of moderate wind speeds and high evaporation rates. Efficiencies of 20 percent can be obtained. This method, however, will not salvage great quantities of water. He reports relative costs of raw water and the table from his paper is reproduced below.

TABLE A1-2

COST OF RAW WATER
(dollars per acre-foot)

Local Runoff	$ 3.00 - 10.00
Ground Water	$ 3.00 - 10.00
Imported Water	Variable
Reclaimed Waste Water	$ 25.00 - 40.00
Sea Water Conversion	
Distillation	$ 250 - 600
Solar Stills	$ 350
Freezing	$ 700
Ion Exchange	$ 8000*
Electrolytic Action	$ 500*
Ion-Permeable Membranes	$ 3000*
Evaporation Suppression	$ 20.00 - 35.00

*Considerably lower for brackish water

Meinke[27] reported on evaporation retardation studies on small reservoirs in Texas. Field tests indicated costs of $1.02 and $2.45 per thousand gallons saved from a 1/6 acre pond. The costs are related to shoreline length, prevailing temperature, relative humidity of the air, water temperature, and prevailing wind velocity at the water surface. The chemical feed rate is related to surface wind speed. The film travels across the pond surface at 3.4 feet for each 100 feet of surface wind travel; when wind speed doubles, feed rate must double. For a given shoreline length then, the pounds of chemical required is simply a function of wind speed. Application should be continuous and at a number of points.

The Bureau of Reclamation[28] made estimates of water losses from evaporation for 1960 and estimates of possible savings for 1960 and 1980 under a full scale treatment program. They estimated that the evaporation losses in the Colorado River Basin in 1960 was 370,000 acre-feet, and that estimated savings under full scale treatment during 1960 and 1980 would be 63,000 and 135,000 acre-feet respectively, at unit costs of $37.00 and $8.00 per acre-foot saved, respectively.

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APPENDIX A-2

REVIEW OF DEVELOPMENTS, METHODS, COSTS AND CONTROLS

PHREATOPHYTES

A-2 PHREATOPHYTES

Interest in this Country regarding phreatophytes and their use of water dates back no more than about 40 years. During these years, several studies have been made that have revealed the very large quantities of water consumptively used by these plants. These large consumptive uses, coupled with large increases in infested acreage, and concurrent increases in water demand, have made phreatophyte losses an acute problem.

Only during the last 6 or 8 years has research activity shifted from studies that were primarily oriented to evaluation of water loss to studies oriented to evaluating control methods and related economic feasibility (salvage value of "saved" water). The investigations are discussed below in chronological order. Several investigations underway are to reveal fundamental knowledge in the field of herbicide control, and these studies have not as yet been reported in the literature.

Meinzer (1) was one of the first to be interested in water use by phreatophytes in this Country and it stemmed from his interest in the plants as indicators of ground water. He is credited with having given the name "phreatophyte" to those plants that "habitually feed on ground water". He discusses specific phreatophytes, but,in general, the value of plants as indicators of ground water conditions is discussed in terms of occurrence, depth to the water table, quality of ground water, and quantity of ground water. The author notes that a person in distress in the desert (thirsty) would not likely find water in areas where mesquite are growing since they generally grow where the water table is 10 to 50 feet deep. On the other hand, the wayfarer may have more luck if he were to dig in an area where salt grass or palm trees were growing,

as their growth indicates that water is within a few feet of the ground surface. The author illustrates the value of beneficial phreatophytes by citing the rise from poverty to relative prosperity of a farmer in Milford, Utah, who recognized the persistent growth of alfalfa (a phreatophyte) under most adverse moisture conditions.

Grover (2) reports on a study to evaluate the occurrence, movement, and quantity of available ground water. In order to estimate the safe pumping yields in certain districts of the Escalante Valley, Utah, the water requirements of the ground water plants in the area had to be accounted for. The diurnal ground water variations were measured for several plants. The water lost by evapotranspiration was ultimately computed by determining the water consumed per pound of dry matter produced (transpiration ratio) in pilot tanks and applying these figures to dry matter production in the field. Studies indicated that, depending on soil cover, water lost by evapotranspiration for each pound of dry salt grass produced varied from 1,950 to 1,350 pounds.

The diurnal fluctuation in river discharge and ground water became the preoccupation of several investigators in the 1930's and Troxell (3) reported on a study of diurnal fluctuations that occurred in the Santa Ana River and adjacent ground water about 1935-36. The author attempted to disprove the concept that the maximum daily discharge rate occurred at the time during the day when the transpiration loss was a minimum. By correlating curves showing diurnal fluctuation of river discharge, adjacent ground water elevation, and air temperature, the author demonstrated that the maximum transpiration rate occurred at the time the ground water table was falling at a maximum rate and that this occurs at the time the air temperature is a maximum and not necessarily at the

time stream flow is a minimum. In the same manner, he showed that the point of minimum transpiration occurs at the point of maximum rate of rise of ground water table. The author believes that "the diurnal cycle found in the ground water table and in the stream represents nothing more than an accumulation curve showing the difference between addition to and extraction from storage."

The effectiveness of phreatophyte control was easily demonstrated by Dunford (4) by observing the variation of the diurnal fluctuation in ground water elevation. He describes the methods used to determine the transpiration losses before and after cutting of stream bank vegetation in a 22-acre water shed on the Coweeta Experimental Forest. Data indicated a virtual elimination of diurnal fluctuation of water table during the growing season immediatedly following cutting. The woody vegetation disposed of in the water shed were not phreatophytes but primarily rhododendrum, azalea, black birch, yellow poplar, red maple, and others. The author concluded that treatment raises the average level of discharge rates in streams, eliminates the diurnal variation in water table, and could be of practical value, particularly during drought years for municipal and industrial water sheds.

One of the early studies in phreatophyte control methods and in water use by phreatophytes was that conducted in the lower Safford Valley in Arizona. Gatewood (5) reported on this study. The Safford Valley study was specifically to determine water savings that could be provided by the removal of salt cedar from the valley. Six analytical methods were used to evaluate the data to determine the amount of "saved"water. It was concluded that 28,000 acre-feet of water were used by vegetation during the 12-month period ending September 30, 1944. The study area comprised

9,303 acres in the 46 mile reach of the Gila River from Thatcher to Calva. Of the total loss, 23,000 acre-feet came from ground water reservoirs and the remainder from precipitation. Salt cedar used 75 percent of the 23,000 acre-feet.

In an attempt to control salt cedar, two methods were used for clearing. One method was to cut trees at ground levels, but after three months the trees were again 2 1/2 feet high. The other method was to burn the growths with a flame thrower, but the plants started growing again the next year. It was thought that for permanent clearing, the roots would have to be removed.

Gatewood believes it is not possible to state how much water would be saved by phreatophyte control because: (1) other natural vegetation would continue to use some water, (2) grasses would have to be planted to control erosion, and they would probably use all the precipitation in addition to using ground water, (3) without grasses, a larger percentage of precipitation would evaporate, and (4) without phreatophytes, the ground water table would rise and more water would be lost to evaporation. He believed that under existing conditions, over a perios of a year or more, salt entering the bottom land in ground water inflow, and the amount leaving the area were about equal. Following clearing, during the ensuing unstable period, probably more salts would enter the reach but then a new equilibrium would be reached and the stream would return to the same salt load. No cost data were presented.

For the study period, and for 100 percent density volume, water use per acre was reported to be for salt cedar 7.4 feet, bacharris 4.7 feet, cottonwood 6.0 feet, and mesquite 3.3 feet.

The diurnal effect of evaportranspiration on Gree River discharge was reported by Thomas (6). Discharge records for the Green River from Linwood to Green River, Utah, for the study period August and September 1948 were analyzed for correlation between diurnal variation in river discharge and air temperature. The diurnal variation of river stage is easily discernible on a stage-time curve, and the same phenomena is evident at each of the four gaging stations at Linwood, Jensen, Ouray, and Green River. Reductions in stage attributed to evapotranspiration losses were as much as 0.02 feet.

The river was divided into several reaches and for each of these, the water surface and flood plain areas were calculated. The extent of phreatophytic growths were determined, and the monthly evapotranspiration at each station computed.

One table showed the estimated average daily evapotranspiration losses along the Green River in September 1948 for each physiographic division. The daily losses from water surfaces was 305 acre-feet, from land surfaces 552 acre-feet, for total daily loss of 857 acre-feet.

Another table was prepared to show monthly ground water inflow to the river at each of the four stations.

Robinson (7) discusses the relation of phreatophytes to water in the Western States, and associates a monetary value with the salvageable water. He points out that the phreatophytic use of water varies a great deal depending on species and depth to the ground water. Greasewood, rabbitbrush, and shadscale in Escalante Valley had used about 2 inches per year from depths of 8 feet to 30 feet, while Safford Valley investigators had estimated that salt cedar growing over a shallow water table under favorable conditions used 7 feet per year. In general, the lower

the water table, the lower the rate of use. It is necessary to know the rate of use in an area before considering salvage or more efficient use.

He tabulates the acreage infested and annual water use by phreatophytes in each of the 17 Western States.

He divides salvage operations into three categories: (1) reduction of water losses, (2) increased efficiency of use, (3) combination of the two. In discussing reduction of vegetation, he cites the Safford Valley study. He also cites the Bureau of Reclamation 1948-49 studies above McMillan Reservoir in New Mexico as being quite successful, where 2, 4-D was used on salt cedar. He mentions the possible lowering of the ground water table which must be accomplished rapidly, or the roots will follow the water down.

Increasing the efficiency of ground water use may be accomplished by substituting beneficial crops such as alfalfa, and grasses. He cites Escalante Valley where alfalfa was substituted for greasewood, rabbitbrush, and salt grass.

He estimates phreatophytic losses in Nevada to be 1,500,000 acre-feet. Of this, 25 percent, or 400,000 acre-feet, is estimated to be salvageable. It would provide enough water to irrigate 133,000 acres, and with an average yield of wheat of 3 tons per acre, at $25 per ton, could gross $10,000,000.

In Arizona, of 1,375,000 acre-feet lost, 700,000 acre-feet is salvageable. Crops of higher value can be grown and the gross value of salvageable water could easily be 20 to 25 million dollars.

Another study on phreatophyte control is reported by Turner (8). A cooperative study was made by the Corps of Engineers and U. S. Geological Survey to determine the effects of clearing phreatophytes

from a proposed 2,000 foot wide flood control channel between Granite Reef and Gillespie Dams in Arizona, a distance of 70 miles. He discusses a method for determining the extent of phreatophyte areal growth and volume density. Field work data were used to evaluate total water use by phreatophytes based upon acreage, growth types, use-factors, and densities. Use-factors were those developed for Safford Valley by Gatewood (5). The depth to the water table was projected to the year 2000 for conditions both with and without Colorado River water. Factors that tended to both raise and lower the water table were discussed. Factors tending to raise the water level were: (1) increased salt content, (2) lower prices for agriculture products, (3) introduction of Colorado River water, (4) prolonged wet cycle, and (5) higher power rates (less pumping). Factors tending to lower the water table were: (1) additional agriculture development, (2) lining of canals in valley, (3) consturction of storage dam, (4) development of mining ore body near Mammoth, (5) lowering of power rates, (6) higher prices for agricultural products, and (7) increased efficiency in application of irrigation water resulting in overall lowering of production costs. No control cost figures were given. The quantitative conclusions of this study are summarized below:

Granite Reef to Gillespie Dams - 2000-foot Wide Channel

Total estimated transpiration at time of investigation	29,000 ac-ft/yr
Estimated average from ground water within channel area from 1950-1999:	
without Colorado River water	22,200 ac-ft/yr
with Colorado River water in 1960	29,900 ac-ft/yr
Estimated average water saving by channel clearing 1950-1999:	
without Colorado River water	16,600 ac-ft/yr
with Colorado River water in 1960	22,400 ac-ft/yr

A discussion by Koogler (9) gives some detail of three projects in New Mexico, designed to evaluate phreatophyte control by using herbicides. In the Carlsbad Project, 100 acres of salt cedar on the McMillan Reservoir delta were sprayed with 2, 4-D at a rate of one pound per acre in September 1948 and a rate of two pounds per acre in May 1949. The spray rate was five gallons per acre; four gallons of water and one gallon of diesel oil. By October 1950, regrowth varied from 1-100 percent and the overall kill was estimated to be 85 percent. The total cost was $12.50 per acre. Another 100-acre test site was sprayed with one pound per acre in 1948 and another 100-acre area in 1949 at two pounds per acre. Neither was as successful as the repeated application during 1948-1949.

A willow control program was studied on the Rio Grande Project in which willows along a 20-mile heavily infested canal were mowed and slashed down. Following spring regrowth in April, the stretch was sprayed with sodium salts of 2, 4-D solution containing 1 1/2 pounds of acid equivalent, one pint of Triton X-100, 5 gallons of diesel oil and 95 gallons of water at a rate of 100 gallons per acre. Average cost was $12.98 per bank mile. About 20 percent of the willows were killed. Small amounts of regrowth were gradually eliminated by continued application of fortified oil.

Cattails and tules in the Rio Grande Project were controlled by spraying spring growths with diesel oil fortified with pentachlorophenol. They were sprayed twice, followed each time by burning so the roots would be reached by the final application of the above, but to which was added 1 1/2 pounds of 2, 4-D. About 84 percent of the bank growth and 60 percent of the cattails were killed. No cost data were given.

The role of the Corps of Engineers in the southwest regarding phreatophyte control is discussed by Cramer (10). He states that as early as 1939, the Corps provided funds to enable the U. S. Geological Survey to investigate consumptive use of water by river-bottom growth in the Gila River in Safford Valley, Arizona. He describes the Corps as a construction agency that has done little investigational or research work on control of this growth and does not anticipate doing any.

He refers to the Corps' work in potential clearing and maintenance of a flood channel from Granite Reef Dam to Gillespie Dam in Arizona. The estimated cost of this clearing is $20 - $150 per acre depending on growth density. Economic justification for all Corps projects is required for Congressional enactment. Benefits accrued from phreatophyte control, therefore, are important and may be gained not only in imcreased flows but also from an improvement in water quality.

Phreatophyte problems in New Mexico are discussed again by Thompson (11) following a listing of the entire gamut of control studies that had been made by various agencies and States from about 1948 to 1956. He states that the most effective herbicide is a mixture of esters of 2, 4-D, and 2, 4, 5-T applied at rates exceeding 2 pounds per acre. The average cost for aerial spraying was reported as $5.32 per acre and was based on analyses of 17 contracts covering the spraying of several thousand acres. Ground spraying from a truck was reported to be $20 per mile of Rio Grande Project. He reports on a cooperative project between the New Mexico State Engineer's Office with the Bureau of Reclamation in the clearing and discing of 4,741 acres in San Marcial area of the Rio Grande Valley. The mechanical clearing was accomplished at a cost of $11.19 per acre. He concludes that channelization may be the most effective means

of salvaging water in reservoirs and river channels, particularly in the heavily silt-laden river basins of the West. He states that the first large-scale water salvage program to be undertaken by the Bureau of Reclamation in the West, which was started in 1951 in the Rio Grande Valley, was a channelization program.

Frost (12) reports on the Wellton-Mohawk salt cedar clearing studies which were to investigate effectiveness, cost, plant succession, and water relationships. Areas were cleared of salt cedar by undercutting with a bulldozer. Records from wells in river beds near the cleared areas were used to study water relationships.

There was a 92 percent total reduction in areal cover and 72 percent reduction in density after one year. There was some crown regrowth in areas with surface water or high ground water. Cost for undercutting was $6 to $30 per acre depending on the amount of vegetation. Cost for raking and stacking salt cedar brush ranged from $7 to $16 per acre. There appeared to be no reinfestation by woody species other than salt cedar. No well records were available prior to clearing so it was not possible to discern effect of clearing upon ground water depth and quality.

Blaney (13) reiterates the need for considering phreatophytic losses in water supply inventories. He states that almost all past studies in phreatophytic losses by Federal and state agencies have been limited in time, and none have been for periods longer than one-half to one year. Therefore, it is usually necessary to estimate consumptive use by empirical formulas. He tabulates and summarizes the results of several field studies showing consumptive uses for several types of phreatophytes, depth to ground water table, and locality (Arizona, California, New Mexico). The areas in the Western basins that are acutely infested with phreatophytes

are on the Colorado, Gila, Rio Grande, and Pecos Rivers. The author refers to the Corps of Engineers' recommendation for clearing 94 miles of Gila River channel from the head of Safford Valley to Buttes Dam site, Arizona. This involves 14,300 acres of phreatophytes with a potential savings of 36,000 acre-feet annually, and the water has a salvage value of $9 per acre-foot. Blaney concludes that more studies are needed to permit the determination of water losses, to improve control methods and salvage efficiency, and to improve management practices.

One of the most recent publications on phreatophyte research is by Robinson (14). The publication contains a summary of all known Federal, state, and university studies on the phreatophyte problem. A total of 48 projects in 8 states are described. Some of the projects are more directly related to salinity control procedures than others. For instance, one project is entitled "Carbohydrate Reserve in Tamarisk". This study shows that applications of various formulations of 2, 4-D and 2, 4, 5-T cause a reduction in the carbohydrate food reserve present in the stem, crown, and root, and that the reserve is associated with the growth, vigor, and susceptibility to injury. These cause and effect relationships, when properly understood, will indicate the advantages for timing a control program with certain stages of development. One project of direct interest was the control study conducted south of Buckeye, Arizona, to test effectiveness of herbicides. Mechanical clearing is advantageous, as shown by this study, when near-by corps would be endangered by spraying. The most effective and practical method for controlling salt cedar is to follow such a clearing program by spraying the regrowth with 2, 4, 5-TP (Silvex) at 4 pounds per acre annually. It is concluded that low volatile esters of 2, 4-D or combinations of 2, 4-D and

2, 4, 5-T have been consistently more effective than sodium salts of 2, 4-D. No cost data were given.

There are many other studies summarized in Robinson's report and there is no need to summarize them here. Some of the projects are reported on periodically in the quarterly meetings of the Phreatophyte Subcommittee of the PSIAC.

One method of phreatophyte control that has been mentioned is that of replacing non-beneficial with beneficial phreatophytes. A variation of this would be to breed domestic crops having the salt tolerant features of halophytes. According to Bonner (15), the possibility of breeding such beneficial and yet salt-tolerant plants, is vanishingly small.

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APPENDIX A-3

REVIEW OF DEVELOPMENTS, METHODS, COSTS AND CONTROLS

DESALINATION

A-3 DESALINATION

The process of saline water conversion in itself is not a salinity control procedure. It can be used, however, and probably will be used to a larger extent in the future, as a source of fresh water, particularly in the Western States. This is true in specific inland areas where brackish water is a problem and on the coasts where for all practical purposes, the sea provides an infinite quantity of water supply. To date, the process has only been used to provide water for municipal and industrial use, and the process is too expensive to consider for "instream" salinity control. None of the desalination processes have been, or are likely to be, developed to the point where they can provide water at current irrigation water prices ($1.00 to $3.00 per acre-foot).

The conversion of saline water to fresh water is not new, but the current quest is for a process to convert large volumes at low costs. Moorehead (1) noted that in 1867 two condensers were used in Zula, Ethiopia, to produce 160 tones of fresh water per day (40,000 gpd) to support the British Army during the invasion of Ethiopia. About the same time, another application was made in Chile (2) in 1870 where a 50,000 square foot solar still was built to supply water to a mining camp. The capacity was probably about 1,000 gpd. These were undoubtedly relatively expensive processes.

Several studies have been made during the last ten years in a basic research program on reducing the unit cost of production. The Saline Water Act of 1952, as amended in 1955 and 1961, has provided considerable money for basic and applied research. However, before discussing the results of this research, each of the conversion processes will be

described briefly. Since some processes are applicable for either brackish or saline water, these latter terms will have the meaning prescribed by Wolman (3) and Faust (4) who agree on the TDS characterizations as follows:

Slightly brackish	1,000 - 3,000 ppm
Moderately brackish	3,000 - 10,000 ppm
Highly brackish	10,000 - 33,000 ppm
Sea water	33,000 - 36,000 ppm
Brine	36,000 - + ppm

Summary of Processes

The processes can be divided into three general categories; vapor, liquid, and solid phase separation processes. The vapor processes include distillation and evaporation. The liquid processes include membranes (osmosis and electrodialysis), solvent extraction, and controlled diffusion. Solid phase processes include freezing, hydrates, ion exchange, and absorption.

The distillation process is being used primarily for desalting sea water (5). The commercially feasible processes are vapor compression distillation, multiple-effect distillation, and flash evaporation. The first process is an application of the heat pump principal where the vapor is compressed with an accompanying increase in temperature and then returned to the evaporator where the water condenses and the liberated heat is used to evaporate more water. The input energy is mechanical rather than thermal, (i.e., for compressor power). Multiple effect distillation employs the use of a series of boiling chambers or "effects". The vapor from the first effect moves to the second effect where it liberates heat and causes evaporation of brine and this is repeated through any number of effects. There is a point of diminishing return as each successive effect evaporates less water than the previous one. Flash evaporation utilizes the principal

that under reduced pressure water will boil at a correspondingly lower temperature. The near-boiling brine losses heat as it passes through each chamber, but the pressures in succeeding chambers are reduced to compensate for the loss in water temperature. The disadvantages in distillation processes are scaling and corrosion. Nevertheless, this process appears to be the most economical for conversion of waters of high salinity.

Solar distillation is very simple in principal. The advantages are that it requires no outside energy, equipment and physical facilities are simple, it requires no moving parts, no pre-treatment is required, and the finished water is of good quality. Scaling is not a problem. The disadvantages are diurnal fluctuation in operation, limitation to location, potential wind and hail damage, and large land area requirements (2). (A rule of thumb is 5,000 acres per acre-foot per day) However, units as large as 100,000 gpd appear reasonable.

The membrane processes are the most promising for conversion of brackish waters (6). The two principal processes are electrodialysis, in which energy is supplied by an electric current, and reverse osmosis, in which energy is supplied as pressure (for sea water about 350 psi to overcome osmotic pressure). Electrodialysis is the only process currently in use for demineralizing brackish waters. The process uses DC electricity to cause migrations of salts and minerals through special ion permeable membranes. Alternate membranes allow only cations or anions to pass, and thus the water in every other compartment is demineralized. It is the most economical process to date for demineralization of brackish waters.

The process whichholds promise for the future is that of freezing (7).

It has the disadvantage of being a solid phase process, and with this the difficult problem of separating frozen crystals from the brine. The advantages are that it is a low energy process, accomplished at atmospheric pressure, and at a low temperature which minimizes problems of scaling and corrosion. Two processes have possibilities for sea water conversion; freezing evaporation and direct refrigerant cooling. In the first, the latent heat of fusion is removed by evaporating a portion of pre-cooled sea water at reduced pressure. The second process involves vaporizing a refrigerant in direct contact with the sea water. It is believed that when certain design features and construction material costs are optimized, fresh water will be economically produced by this method.

Several other processes are under investigation but do not appear to have the potential of those processes mentioned above. One of these is the solvent extraction process (6) in which an organic solvent is used to extract water from a brine solution. The solvent is then separated from the water by changing temperature. Another method is the hydrate process (6) whereby low-molecular-weight hydrocarbons, or their halogen derivatives, are used to combine with water and form solid clathrate substances. Clathrates reject ionic substances and accept only pure water as the hydrate crystals are formed. This is similar to ice crystal formation except that it is a molecule in which one substance is included in the crystal lattice of another substance. The crystals are then separated from the saline liquor and decomposed for fresh water production.

Economic Considerations

The cost of producing fresh water from saline water is easily computed for each particular pilot project and for commercial enterprises.

Initially, however, the costs were not being itemized in similar methods, and it was difficult to compare costs. The Office of Saline Water in 1956 worked out a standard procedure (8) for estimating cost so there could be a base for comparing operating costs at the various plants. This method does not include distribution costs.

Aside from determining the actual dollars and cents cost of producing the water, however, is the problem of determining when, where, and whether desalination is cheaper than importing acceptable water. Koenig (9) has reported on his studies in this area of economic boundaries. The basic question in many communities, in their search for a water supply source, is, "is it cheaper to desalinize a local saline supply or to import a more conventionally acceptable water?" The elements of conventional water systems and costs that are influenced by saline water conversion are the intake, raw-water storage, transmission, and treatment. Koenig summarizes, "the sum of the costs of those components eliminated by saline water conversion, less those incurred by the saline water source, is the 'break even cost for conversion' or the highest cost that conversion can reach and still compete with conventional supplies." He develops a "break even" curve for a given situation to show that for increasing increments in water demand, a town can economically transport water over longer distances. This line of reasoning leads to the conclusion that saline water conversion in a growing community is a self-annihilating operation, because as the water demand increases, the value is eventually reached at which it is more economical to import fresh water than to convert an equal quantity of local saline water. Koenig believes that for saline water conversion to have a lasting impact on water supply problems, the cost-capacity curve will require a greater slope and thereby

approach the slope of cost-capacity curves for conventional supply techniques. He leaves the definite impression that for large quantities of water, it will be cheaper to import than to desalinate local supplies because of the rapid decrease in cost of transporting large water quantities.

As always, there are two schools of thought and Othmer (10) states that the billions of dollars that Californians are spending to transport water over 4,000 foot mountains and a distance of 750 miles is very expensive, and no other water system as expensive will ever again be undertaken to bring water from such a distance to the seacoast. Using Los Angeles as an example, he states that desalination plants could be built much faster than the long aqueducts and that water could be supplied at $0.40-0.45/1,000 gallons. He states that transported water to Los Angeles now costs about $0.50/1,000 gallons.

A less encouraging picture of the future of saline water conversion is painted by Morris (11). He states that with the California multiple-purpose water program, the cost of water at the Delta is only 1.075¢/1,000 gallons. He believes that in San Joaquin Valley, fresh water from the sea would have to compete with this cost. This of course, is not possible at present power costs.

Applications

Pilot Plants - (6) (12) (13) The 1961 amendment to the Saline Water Act of 1952 authorized $75,000,000 for research and development, but nothing for construction. A separate authorization, enacted in 1958 in the form of a joint resolution, provided $10,000,000 for the construction of five demonstration plants. Four of the demonstration plants authorized have been built and are in operation. These plants are

briefly described below. The fifth plant was redesignated a pilot plant because of its experimental nature, and its construction is nearly complete at Wrightsville Beach, North Carolina. The pilot plant will utilize a freezing process although other processes may also be investigated. The four demonstration plants are as follows:

1. Freeport, Texas; a 1 mgd capacity, multiple-effect, long tube vertical salt water plant. The brine effluent concentration increases about fourfold. Product water has less than 50 ppm TDS and at times less than 10 ppm. Scale control is the main problem.

2. San Diego, California; a 1 mgd multistage flash evaporation sea water plant. It was designed for one million gallons a day at 190°F, but operated at 1,400,000 gpd at 250°F. This plant is considered the most successful of the four plants, (this plant was moved to Guantanamo Naval Base in Cuba in 1964).

3. Webster, South Dakota; a 250,000 gpd electrodialysis plant for brackish water (1,800 ppm TDS). Water pretreatment includes removal of iron and manganese, typical month's cost per thousand gallons are: electric power 4.9¢, chemical 7.2¢, membrane and other replacements 11.6¢, for a total of 23.7¢.

4. Roswell, New Mexico; a one mgd vapor compression plant for highly brackish water (15,860 ppm TDS).

Commercial Uses

Several other plants have been constructed as commercial enterprises in the United States. There are plants at Coalinga, California (14), Morro Bay Power Plant near Morro Rock in San Luis Obispo County, California (15), three plants in Florida (16), Gettysburg Air Force Base (17), Virgin Islands (18), and Buckeye, Arizona (19). These are only a few of the plants as there are more than 100 electrodialysis units installed around the world to produce fresh water from brackish water (1,000-5,000 ppm) (20). The costs of many of these plants are summarized in Table 1.

A distillation plant in the Virgin Islands (18) was built to

TABLE A-3-1

SUMMARY OF OPERATING COSTS

	Florida								
	Morton County	Brevard County	Sarasota County	Gettysburg S. Dakota		Coalinga Calif.	Virgin Islands	Morro Bay Calif.	Buckeye Ariz.
Type	Electro-dialysis	Electro-dialysis	Electro-dialysis	Electro-dialysis		Electro-dialysis	Flash Evapor.	Submerged tube Evapor.	Electro-dialysis
TDS Raw Water (ppm)	1225	2053	2169	1900	1900	2392	Sea Water	Sea Water	2140
TDS Finished Water (ppm)	-	-	-	500	920	402	5	50	484
Capacity (gpd)	2 mgd	2 mgd	2 mgd	40,000	-	28,000	275,000	144,000	650,000
Capital Cost (1000 dollars)	$ 650	$ 1150	$ 1400	$ 69	-	$ 105	-	-	$ 305
Unit Cost (dollars/1000 gals.)									
Operating Cost									
Electricity	0.081	0.175	0.200	0.18	0.11	0.21	0.085[a]	-	0.129
Chemicals	0.04	0.036	0.046	0.09	0.09	0.06	0.12	-	0.06
Prefiltration	0.03	0.030	0.030	-	-	-	-	-	-
Fuel	-	-	-	-	-	-	0.372[b]	-	-
Maintenance (dollars/1000 gals.)									
Membranes	0.038	0.066	0.084	0.13	0.13	0.23	-	-	0.075
Labor	0.014	0.025	0.030	0.27	0.27	0.17	0.05	-	0.069
Other Equipment	0.011	0.016	0.019	0.03	0.03	0.03	0.05	-	0.064
Filters	-	-	-	-	-	0.19	-	-	0.032
Amortization	0.064[d]	0.112	0.136	0.35	0.35	0.54	0.39	-	0.255
Total Cost/1000 gallons	$ 0.278	$0.460	$ 0.545	$ 1.05	$0.98	$1.43	$ 1.067	$ 1.20[c]	$0.63

a/ 8 mills/kwhr
b/ based on 25¢/1,000,000 BTU
c/ @ 100% capacity & fuel cost 35¢/1,000,000 BTU
d/ Florida plants amortization specified @ 5% over 25 years

replace water supply that was costing about $5.00/1,000 gallons. Anticipated cost was $1.75/1,000 gallons. Based on the standards of OSW, the cost is $1.07/1,000 gallons, but the actual cost is about $2.17, the price charged to the customers.

The first land based water evaporation plant in the United States was constructed at Morro Bay in 1953. It was a submerged tube evaporator type. It operated successfully for the five years of record with total cost of production of $2.50/1,000 gallons (if operated at full capacity).

Barnhill (16) reports on three, 2 mgd electrodialysis units used to treat brackish waters in Florida (1,200-2,200 ppm TDS). He estimates, based on 2 mgd capacity, that the cost varies from $0.278 to $0.545/1,000 gallons. He states that the cost range will be reduced to 10¢-30¢ in the next three years.

Electrolytic demineralization of brackish water (2,100 ppm) at Gettysburg Air Force Station is reported by Pruel (17). The plant was placed in service in 1959, operates at a cost of $0.98/1,000 gallons and the water is reduced to 920 ppm. He states that this is half of the cost of the estimated product cost for a standard bed-type ion exchange plant. He believes that the water can actually be produced at less than $0.98/1,000 gallons.

The cost of the electrodialysis plant at Buckeye, Arizona, has recently been reviewed by Hamner (19). The plant has a capacity of 650,000 gpd. The present cost is $0.63/1,000 gallons. However, the plant operated much of the time below the rated capacity. The cost would be $0.32/1,000 gallons if the plant could operate at full load.

A very large distillation plant is proposed in the Southwest Water Plan (21) as an alternative plan to provide 1.2 million acre-feet annually

for the projected municipal and industrial water use in central Arizona. The desalting plant would be located in Yuma and would cost about $900,000,000 for desalting plants, intakes, and return channels, but exclusive of associated thermoelectric generating plants. It would consist of several (nine) 150 mgd plants, each combined with a thermoelectric power plant (417 MWHR generator stations, net for sale). The investment cost would be $86,000,000 for the water plant and water cost would be $0.28/1,000 gallons. Of this, $0.10 is capital cost and $0.13 is energy cost. These costs are for a coal-fired electric power plant. Gas-fired plant would result in unit cost of $0.32/1,000 gallons. The conversion plant in both cases would be a multistage flash evaporization process. It was proposed that a smaller prototype of 50 mgd would be constructed prior to constructing the larger plants.

Summary

In summary, the future of saline water conversion in providing high quality water will be limited to the area of "water treatment," and is not likely to be used as a salinity control procedure for maintaining "in-stream" water quality. It will be used to provide water that is sold directly to users that can afford high cost water. To date, the electrodialytic process has been profitably used in areas where relatively small volumes of brackish water require treatment (2 mgd, 4,000 ppm TDS). Costs range from $0.50 to $1.50/1,000 gallons. In many instances, consumers had been paying more than ten times this cost for potable water.

Desalination of sea water is best accomplished by a distillation process. The costs are in the same range as for the membrane process. Low rates of $0.30/1,000 gallons are anticipated for large plants. Large plants are generally restricted to coastal areas because there are large

quantities of salt water available at low heads and the problem of brine disposal is small compared to inland plants.

Desalination of local saline waters will be cheaper in some situations than importing potable water. Many projects now exist that will provide considerable data on operation and capital costs for operating smaller units.

Very large plants to be operated in conjunction with large thermal power plants, have been proposed in the Southwest Water Plan. A plant as large as 50 mgd has been proposed as a step to the ultimate construction of a 150,000,000 gallon plant, and then the construction of a 1.35 billion gpd complex of these plants. Water costs are expected to reach lows of $0.28-0.30/1,000 gallons in this size range.

It is not anticipated that the cost of producing water by desalination will ever be reduced to that required for irrigation use.

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